Interfacing the instrument and data analysis pipeline developments for the observation of primordial CMB B modes with LiteBIRD

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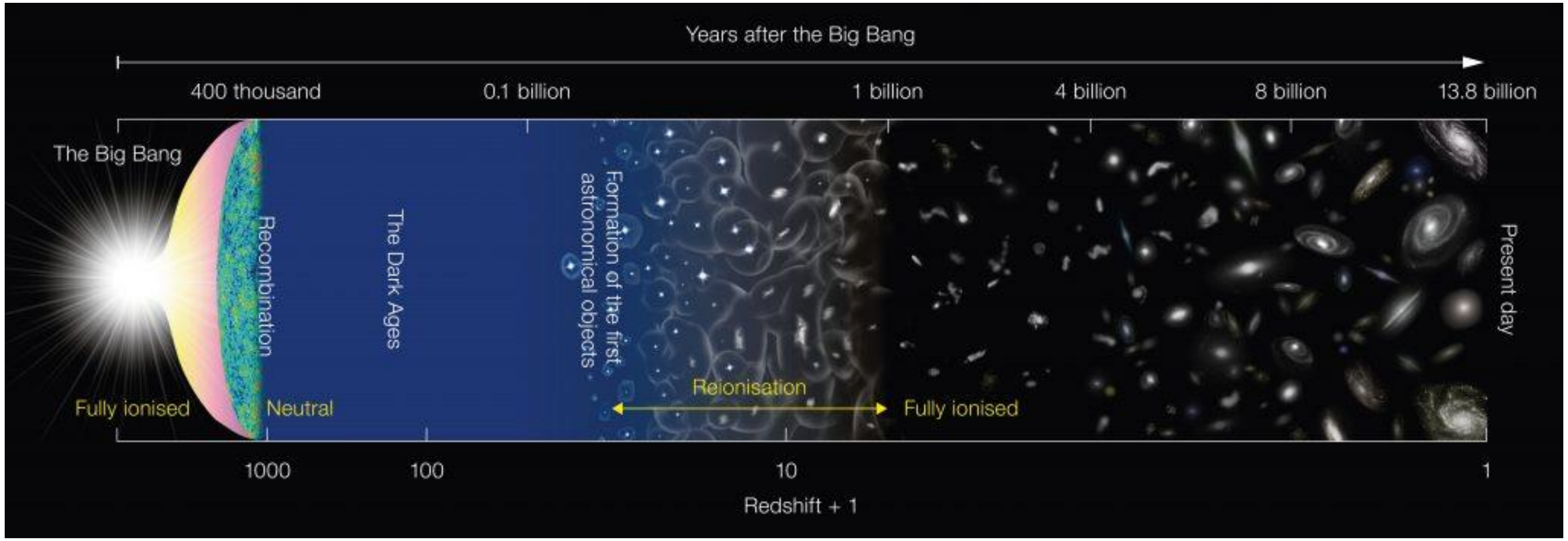
The context

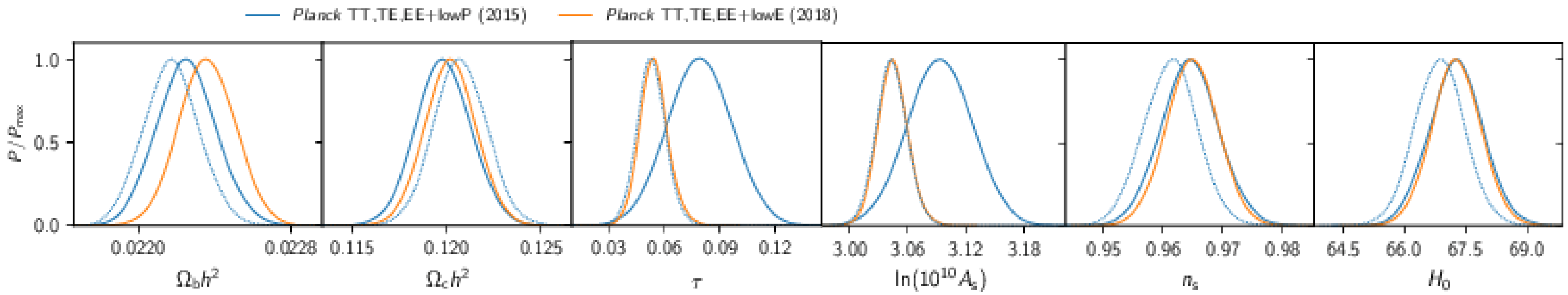
Cosmological concordance model

Clear picture of the history of the Universe, with few parameters:

- Ω_c: CDM energy density
- Ω_b: baryonic matter energy density
- H_0: Hubble parameter today
- τ: optical depth of reionization
- n_s: running of primordial scalar perturbations
- A_s: amplitude of primordial scalar perturbations



Credits: NAOJ

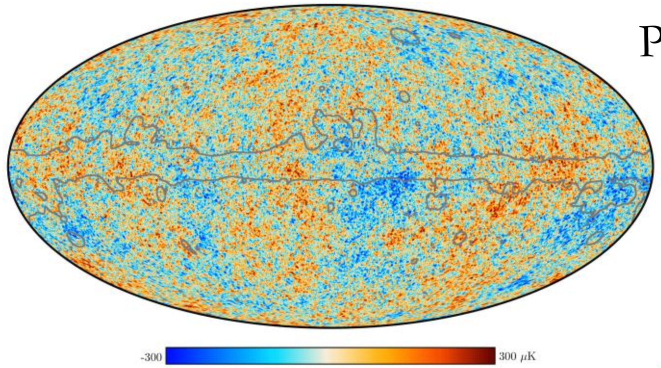


Planck 2018. VI.

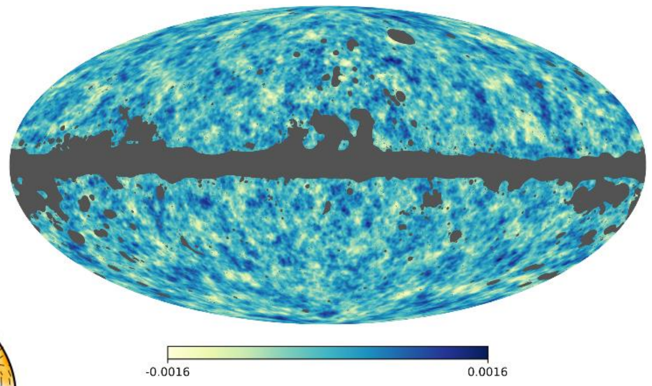
Contribution from CMB

Observations of the Cosmic Microwave Background played a fundamental role

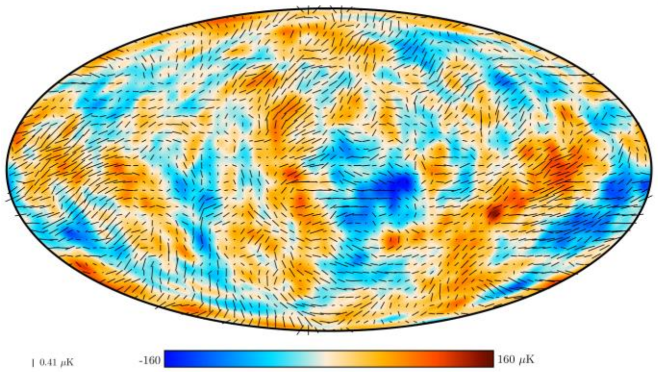
Planck Collaboration



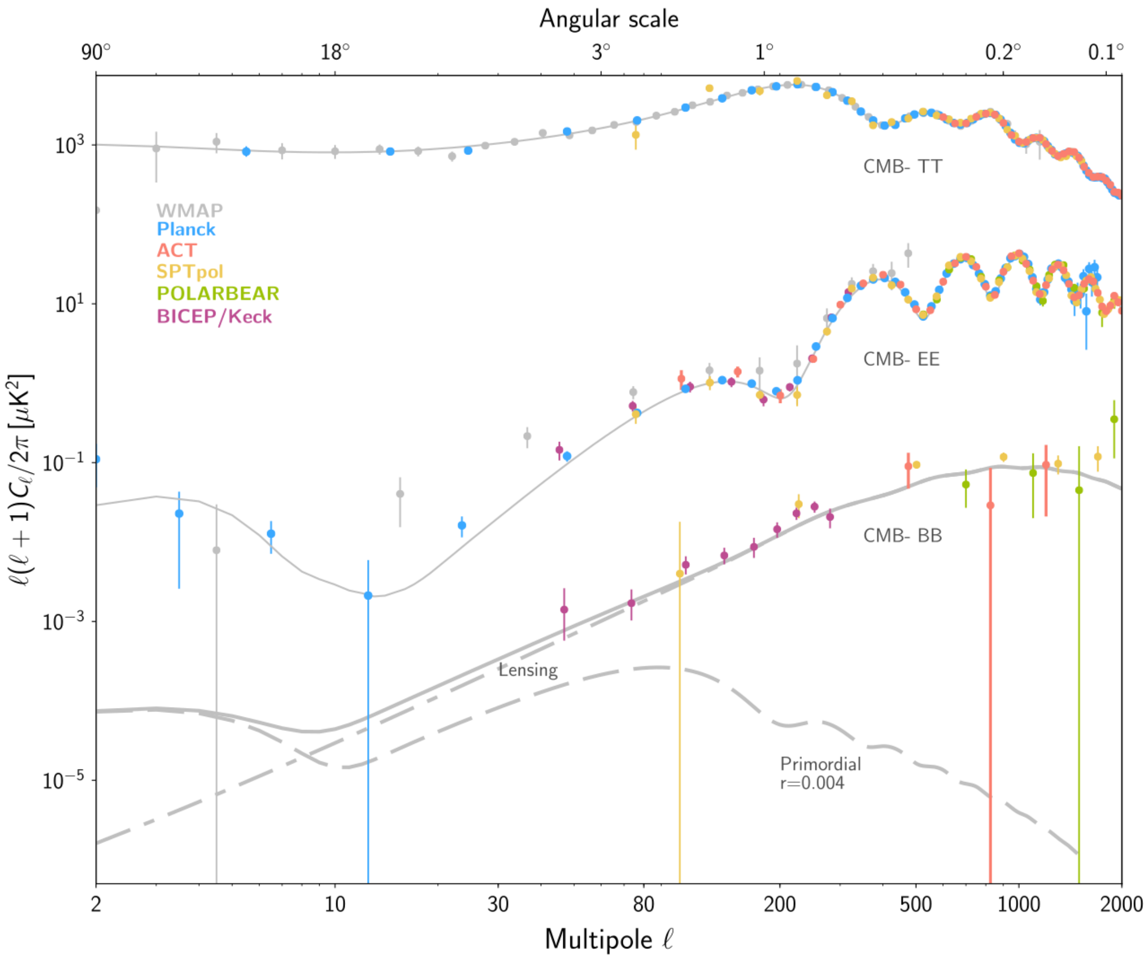
Temperature



Lensing



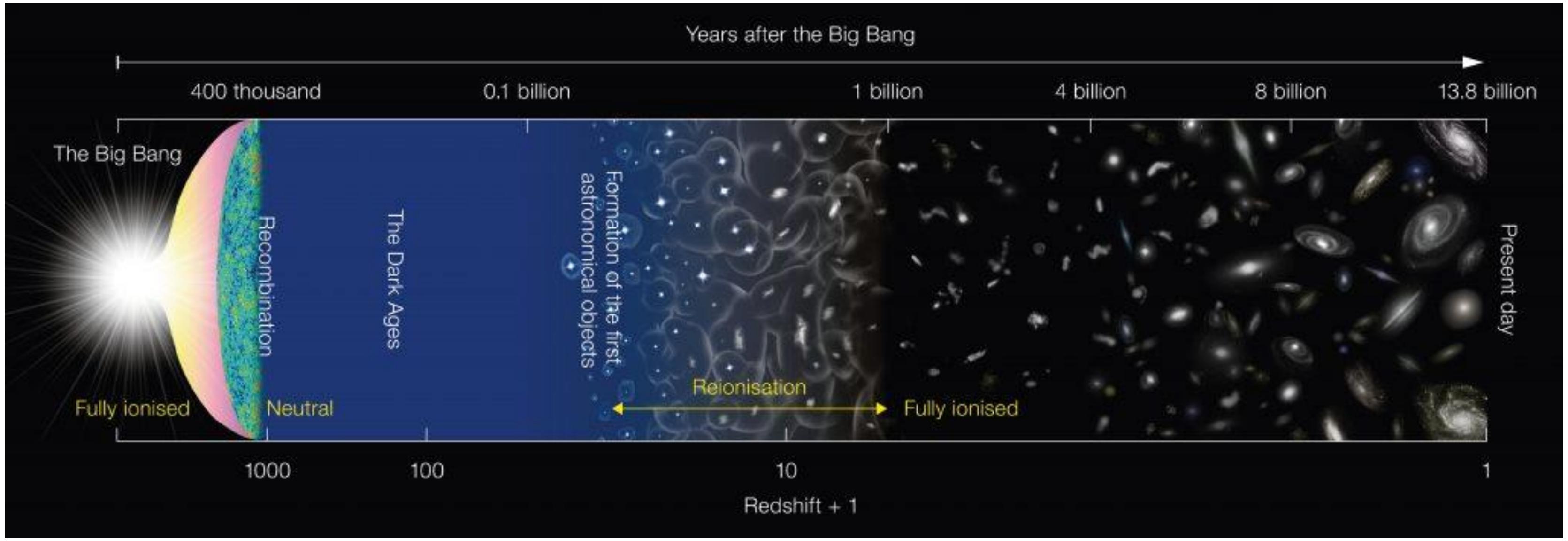
Polarization



Cosmological concordance model

Important fundamental questions remain:

- Nature or Dark Matter
- Origin of the late acceleration of the expansion
- History of the early Universe before BBN
- …



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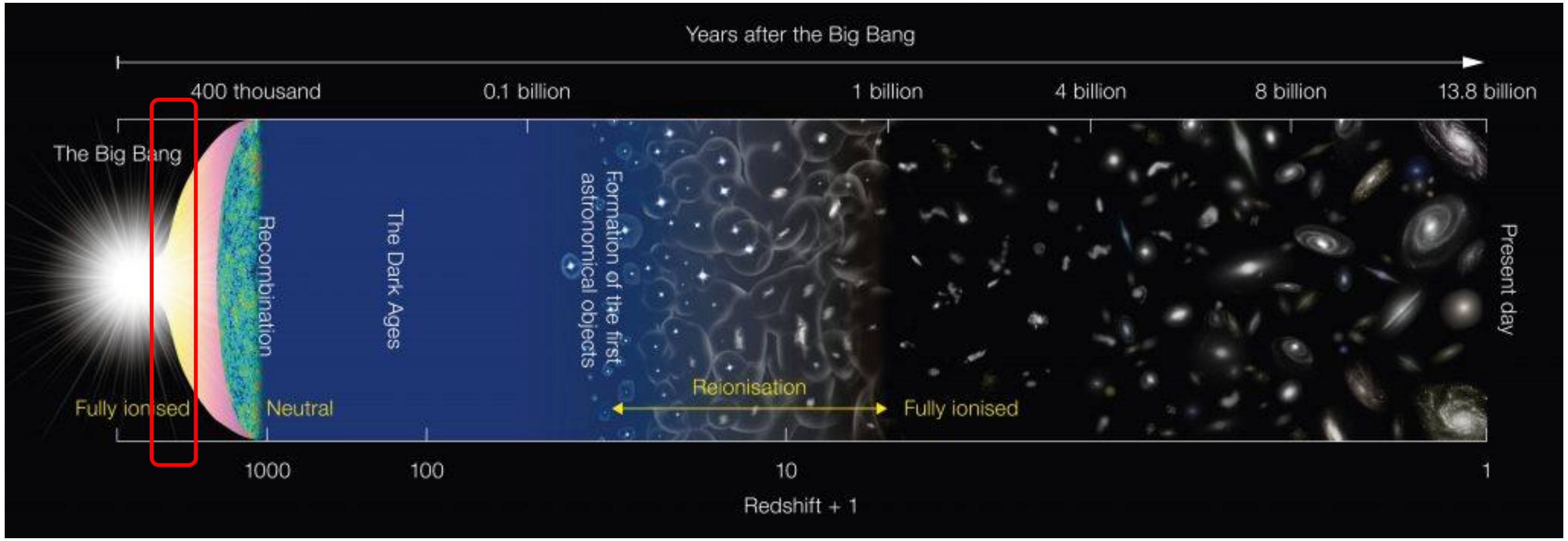

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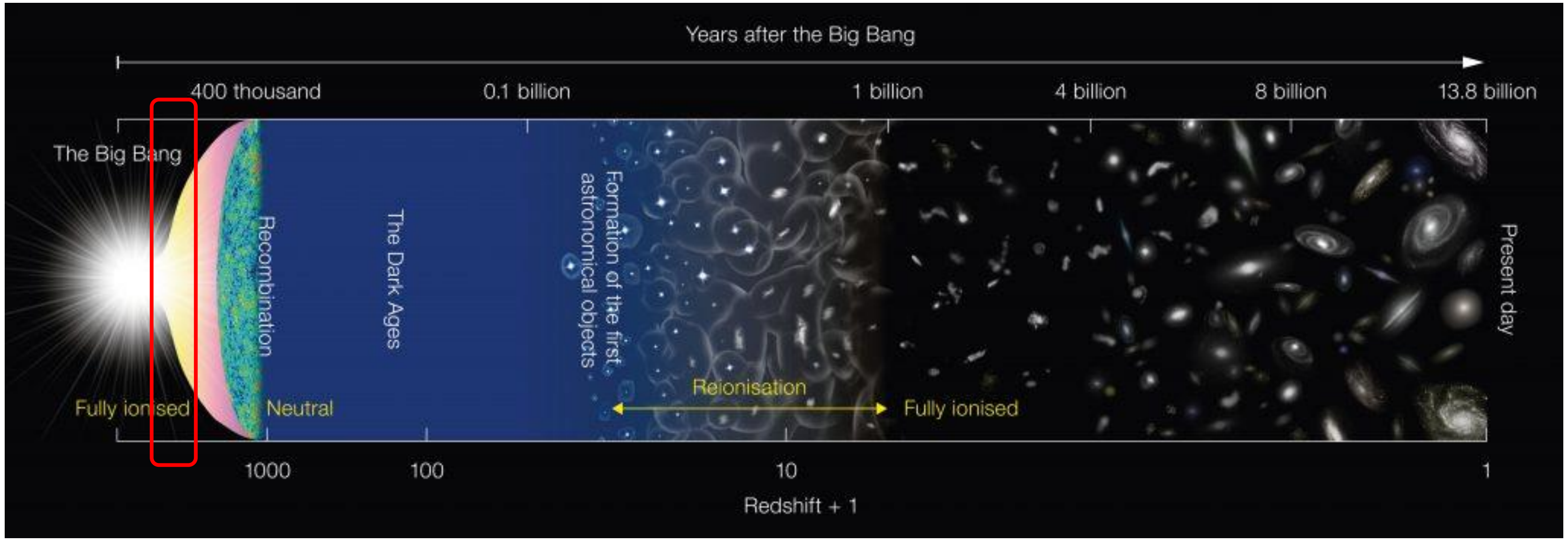


Credits: NAOJ

➢Cosmic inflation is the most popular scenario, currently indirect hints

➢We need stronger evidence to be convinced !

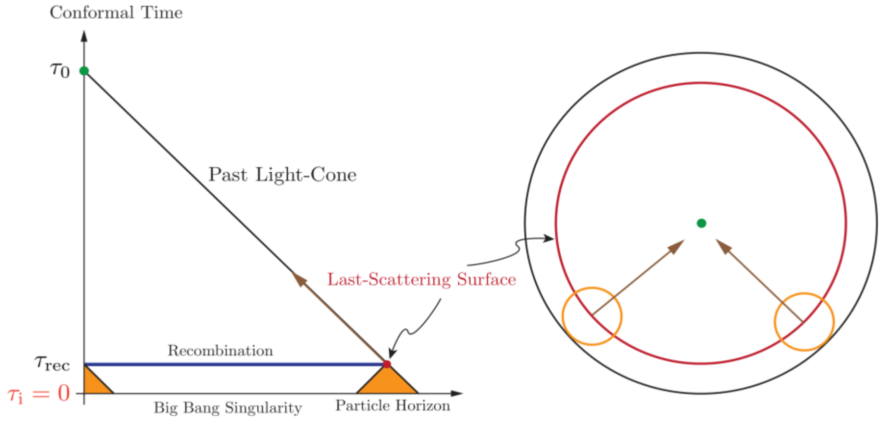
Cosmic inflation

Important fundamental questions remain:

1. Why the Universe appears so flat ?

   $\Omega_k^0 = 0.0007 \pm 0.0019$ (Planck 2018 + BAO)

2. Why the Universe is so homogeneous at large scales ?



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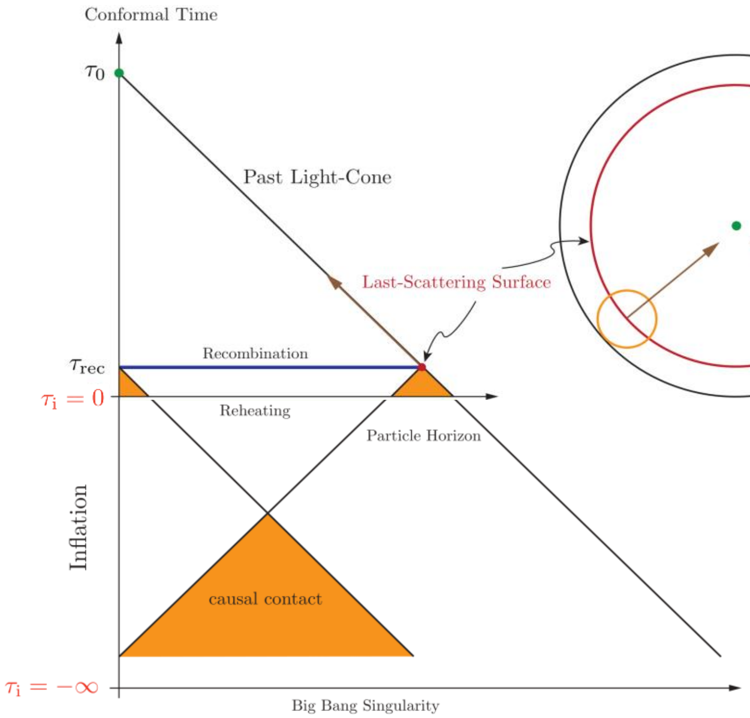
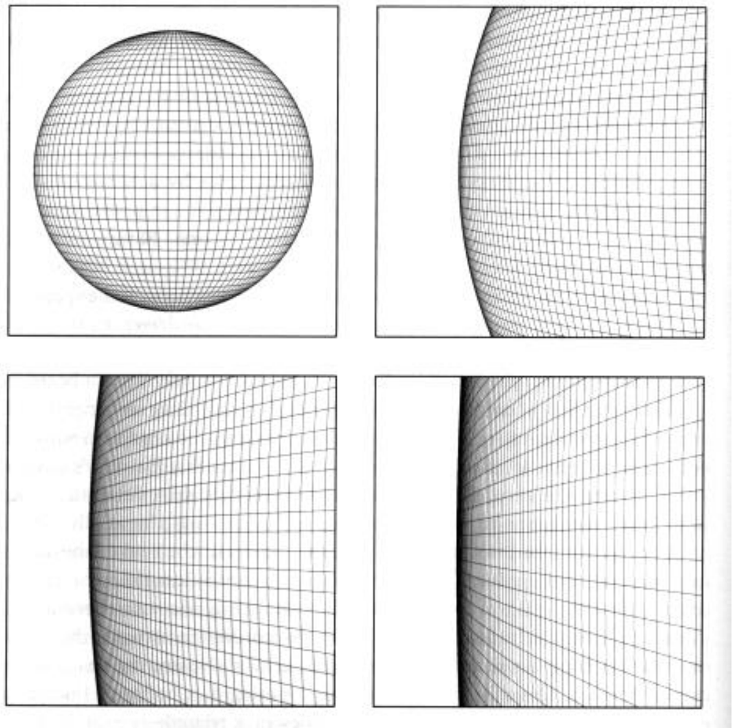


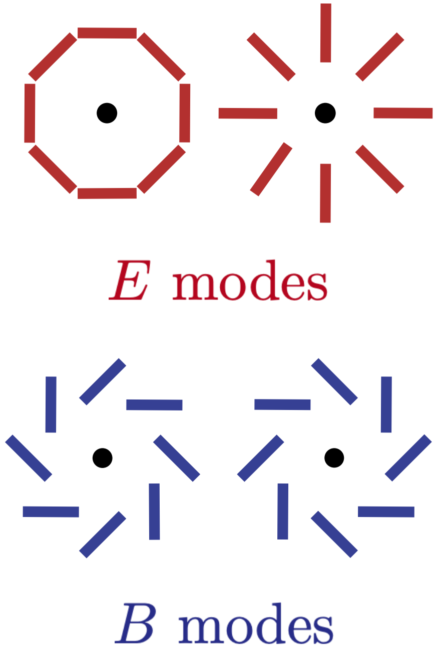


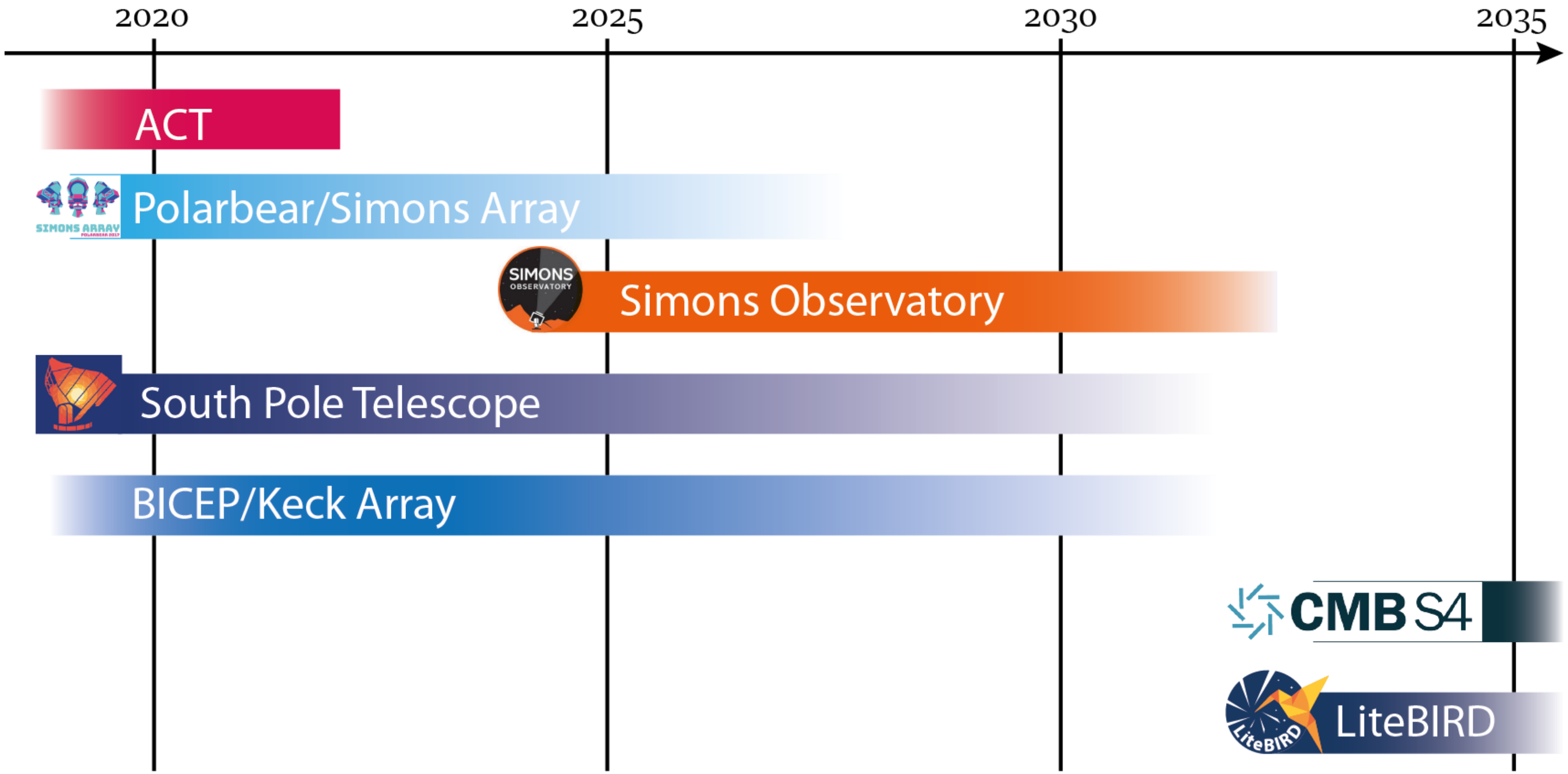
By introducing an era of accelerated expansion, inflation solves these problems

Credits: Daniel Baumann

Future CMB experiments

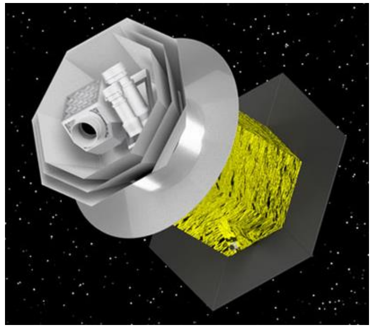
Cosmic inflation generates tensor perturbations that can be observed as B modes of polarization in the CMB

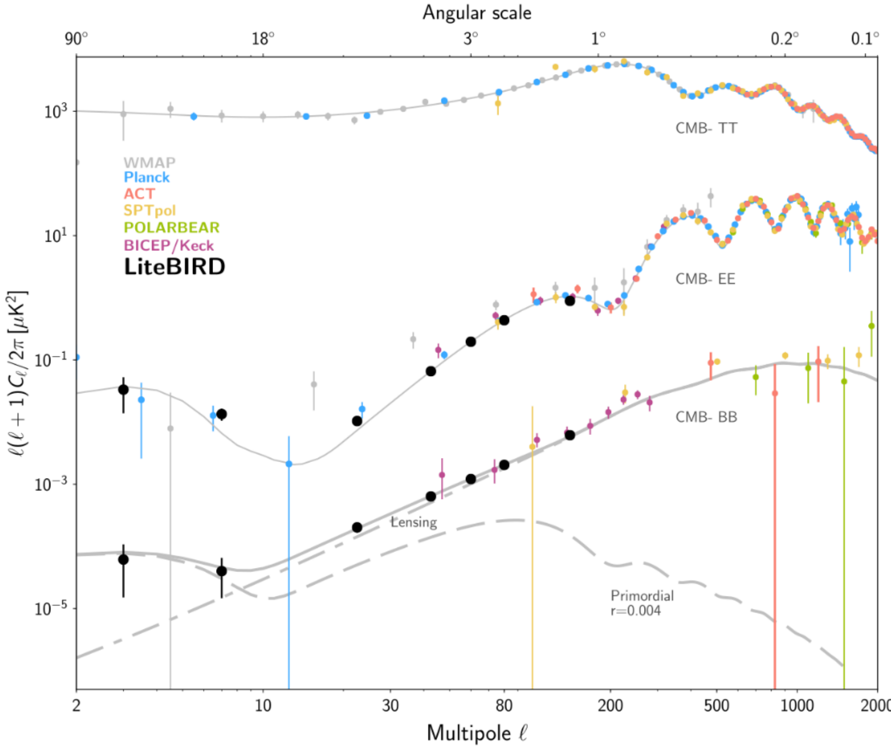


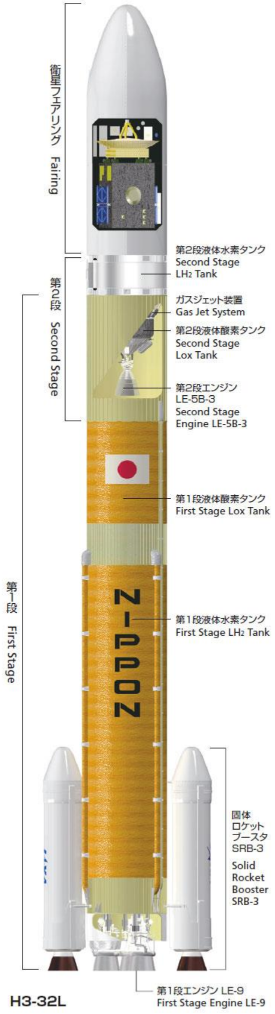


LiteBIRD overview

- Lite (Light) satellite for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission selected in 2019, expected launch in **2032**
- Currently in CNES Phase-A for the MHFT
- All-sky 3-year survey, from Sun-Earth Lagrangian point L2
- Final combined sensitivity: **2.2 μK·arcmin**
- The inflationary (i.e. primordial) *B*-mode power is proportional to the **tensor-to-scalar ratio, *r***
- Current best constraint: $r < 0.032$ (95% C.L.) (📖 Tristram et al. 2021)
- LiteBIRD will have a sensitivity on r **improved by ~50**
- Scientific target without external data:
  - For $r = 0$, **total uncertainty of $\delta r < 0.001$**
  - For $r = 0.01$, 5-σ detection of the reionization ($2 < \ell < 10$) and recombination ($11 < \ell < 200$) peaks independently



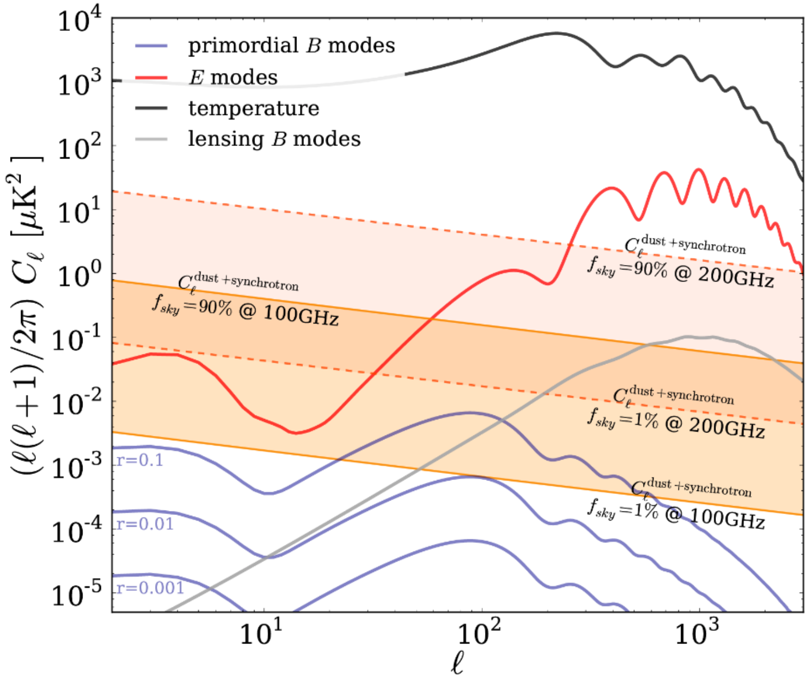




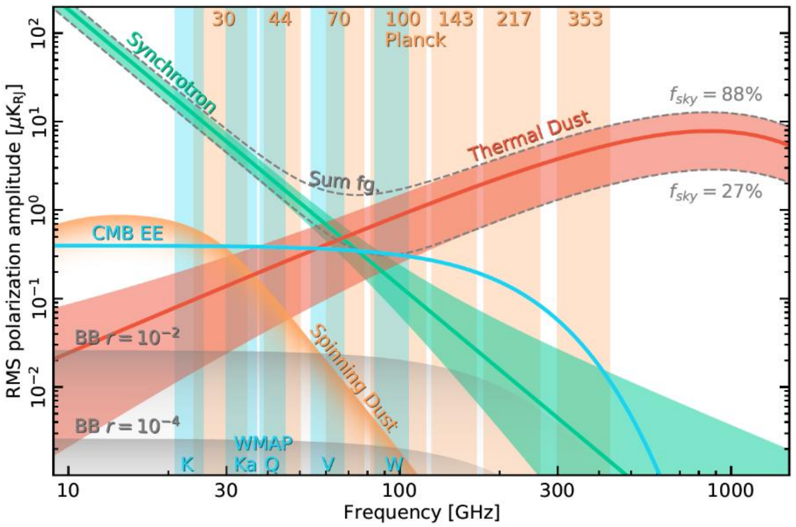
The project

Challenges of B modes in space

Observing primordial B modes is challenging, the problem of foregrounds

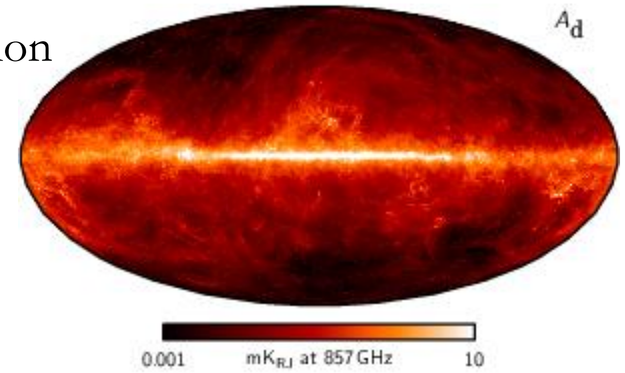


Credits: Josquin Errard

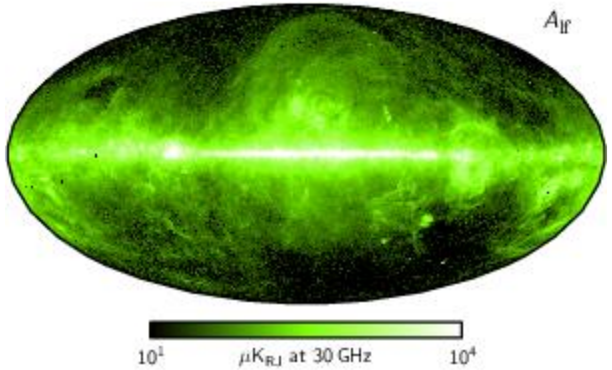


Credits: BeyondPlanck

Planck Collaboration



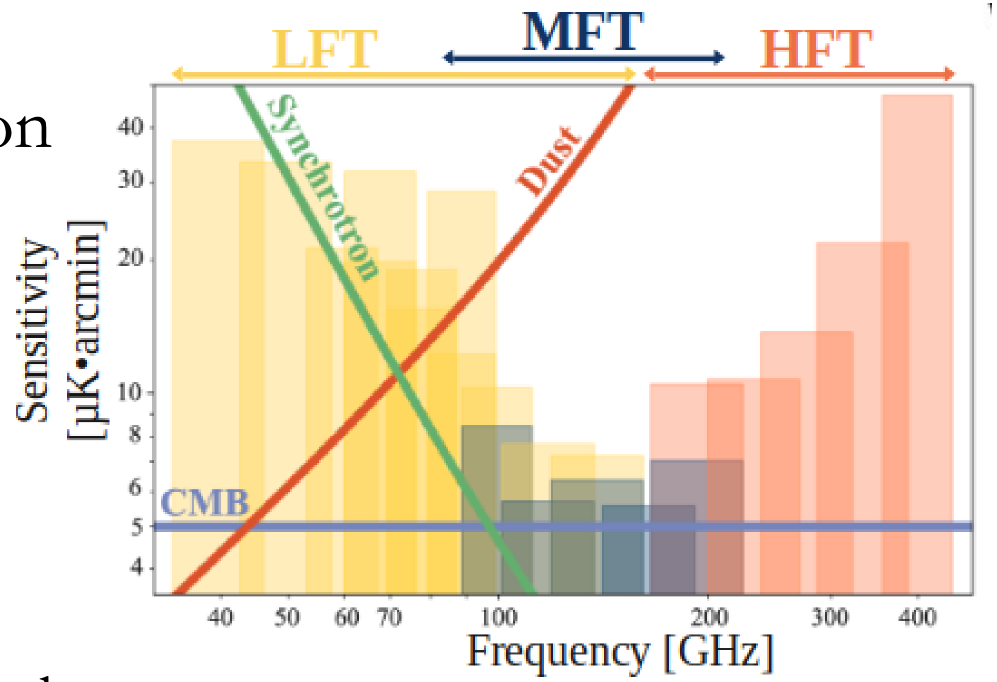
Dust



Synchrotron

Challenges of B modes in space

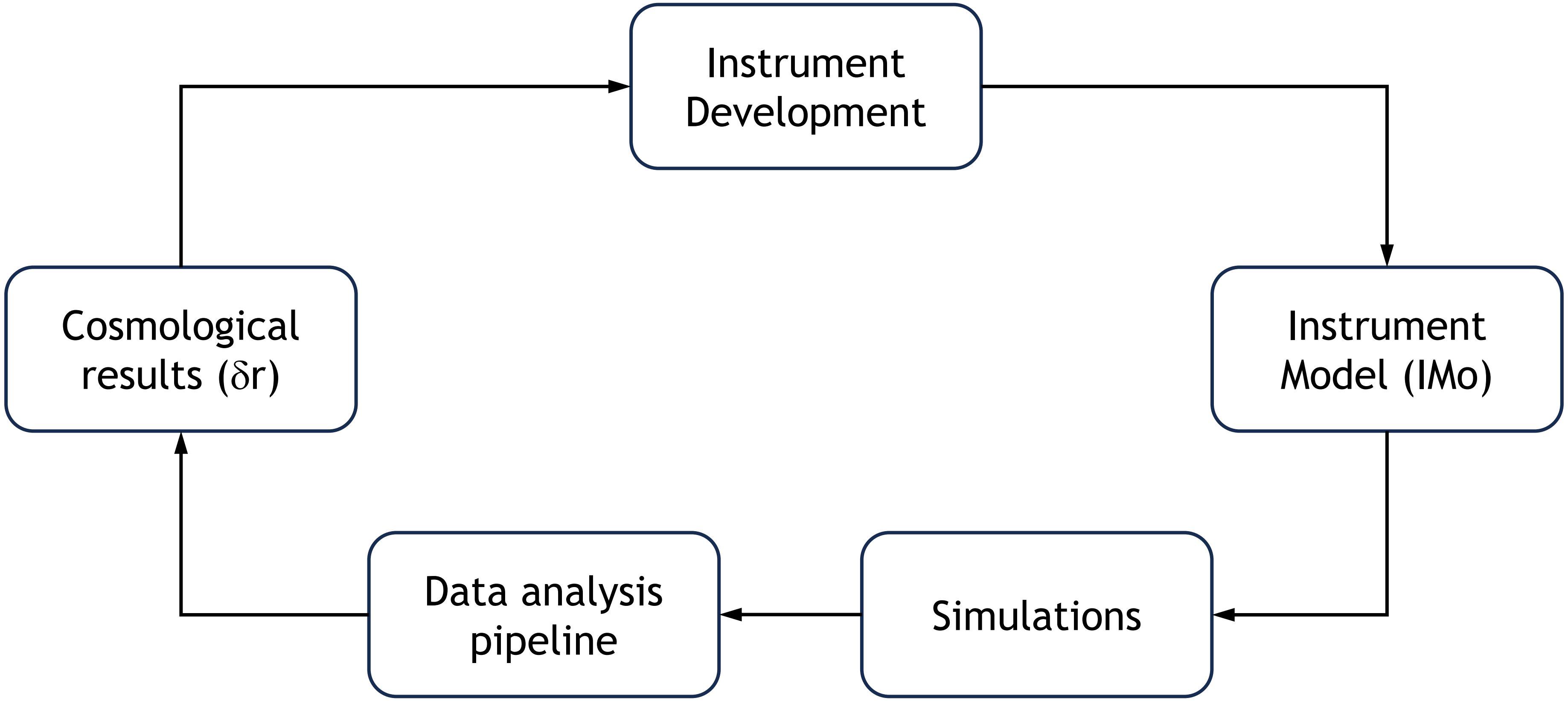
- Going to space allow for a better characterization of the foregrounds



- But comes with its challenges:
  - Important effect of cosmic rays
  - Almost everything needs to be decided prior to launch (not possible to make upgrades)
  - Difficult calibration on the ground and in-flight

Challenges of B modes in space

➢These challenges conspire against us, so the typical pipeline at this stage is:



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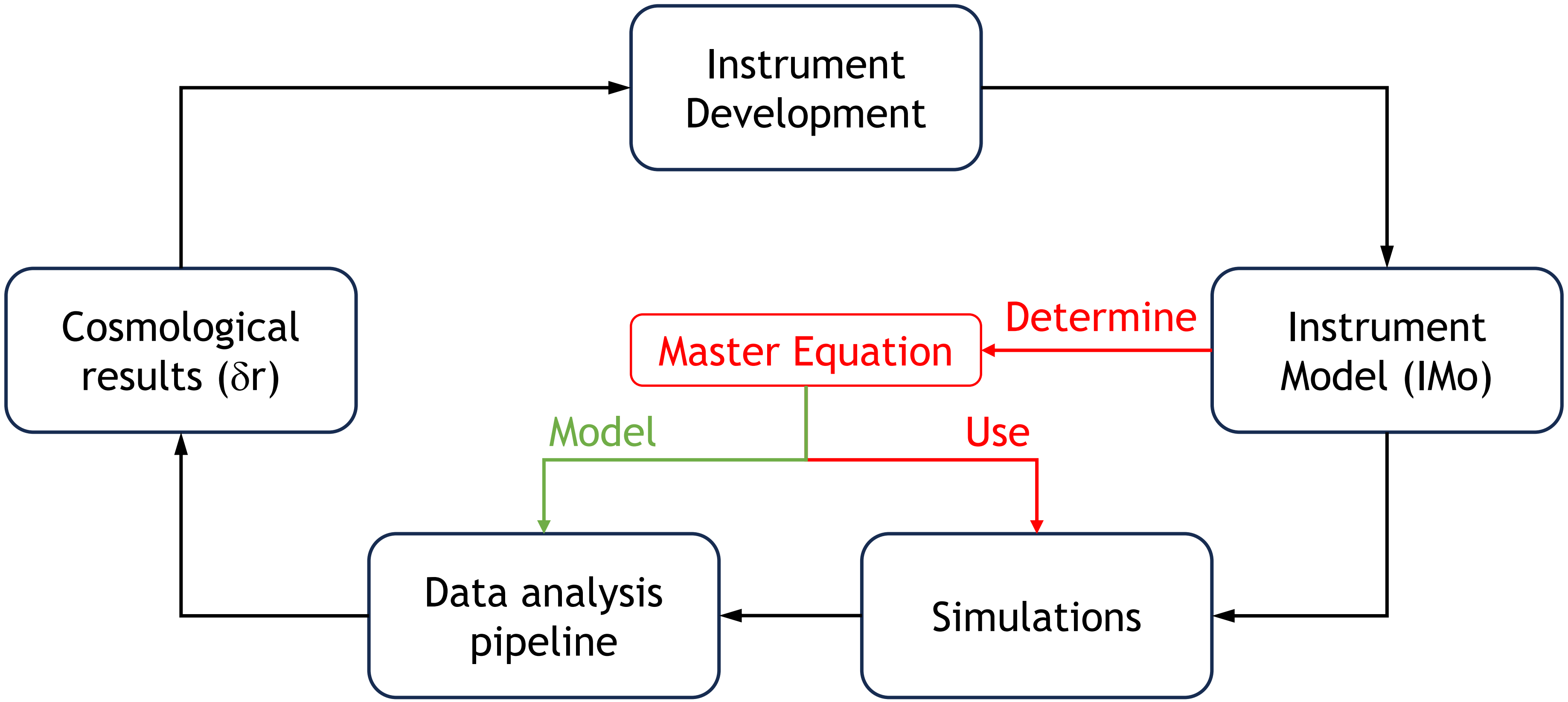
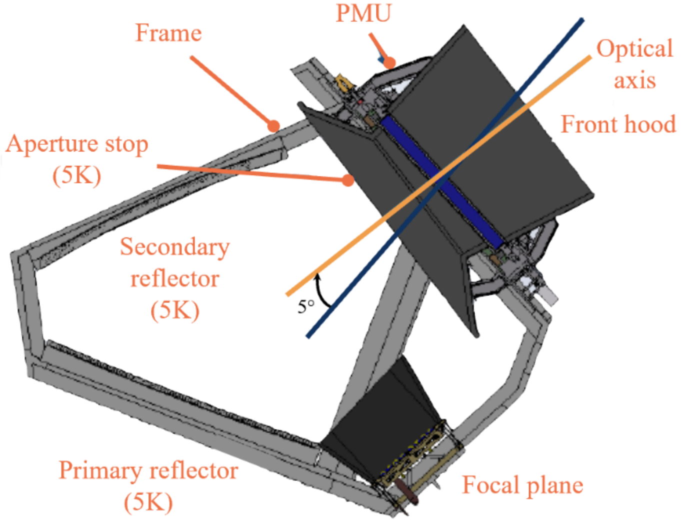


Master equation: describe the full response of the instrument

The master equation

- Correctly characterizing the master equation is critical for the mission
- It is described in terms of Mueller matrices operating on Stokes vectors (I,Q,U,V):



LFT

$$\vec{S}_{out,i} \approx \mathcal{D}_i \mathcal{F}_t \mathcal{O}_i \mathcal{M}_{RAHWP} \mathcal{F}_{b,i} R_i(\psi) \vec{S}_{in}$$

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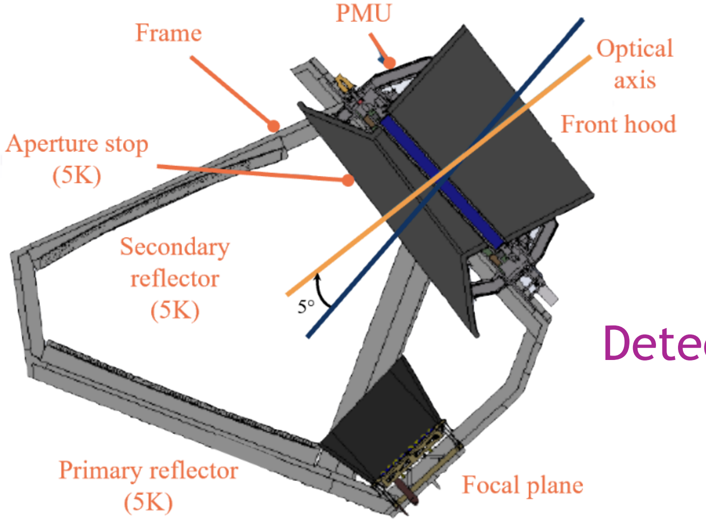

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$$\vec{S}_{out,i} \approx \mathcal{D}_i \mathcal{F}_t \mathcal{O}_i \mathcal{M}_{RAHWP} \mathcal{F}_{b,i} R_i(\psi) \vec{S}_{in}$$

- $\mathcal{D}_i$: Detector system
- $\mathcal{F}_t$: Filters
- $\mathcal{O}_i$: Optical system
- $\mathcal{M}_{RAHWP}$: Rotating achromatic Half-wave plate
- $\mathcal{F}_{b,i}$: Forebaffles
- $R_i(\psi)$: Rotation of the telescope (pointing)

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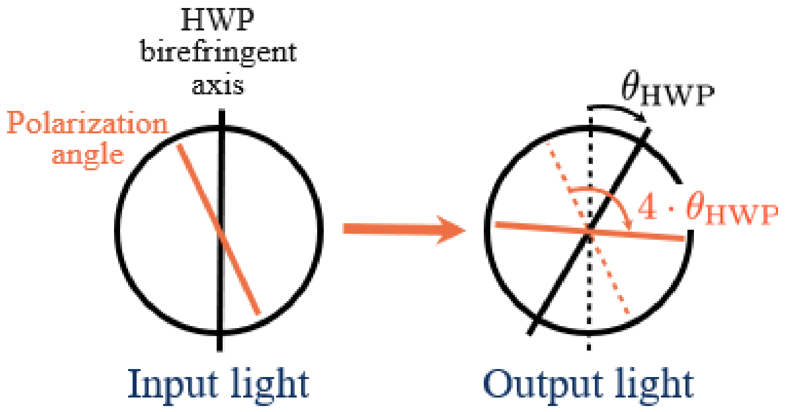
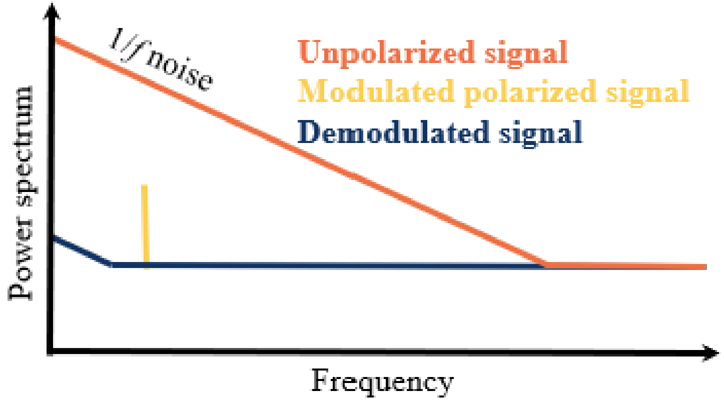
- Each element of these matrices is a function of frequency and position
- The detector system induce an integration over the bandpasses and beams
- This neglect higher order interactions when light gets reflected

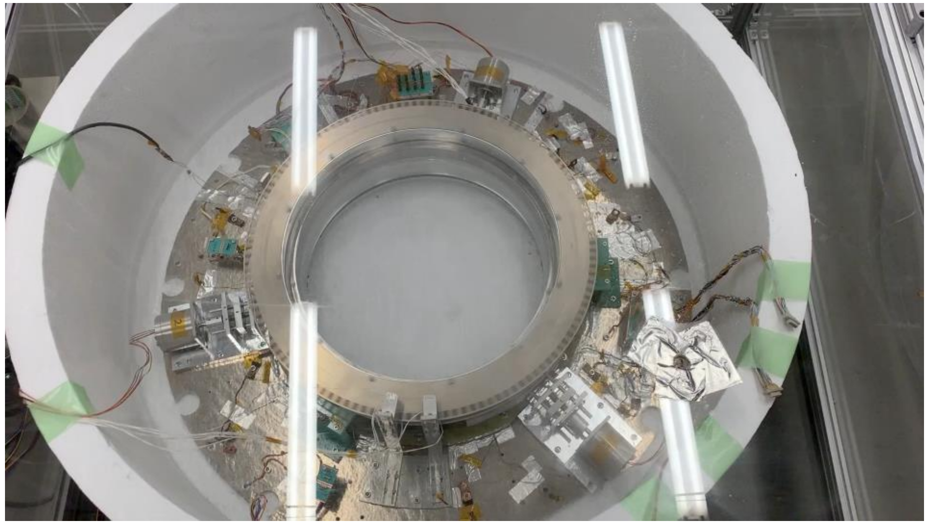
- As a first step, we **focus on the RAHWP**

Rotating Half-Wave Plate

- Rotating a birefringent plate to modulate polarization and reduce systematics
- The first sky-side optical element







LFT PMU at Kavli IPMU

- Rotation with superconducting magnetic bearing
- Stable rotation at cryogenic temperature (10K)

Data analysis side

- The data analysis interpretation of the master equation is the data model
- Ultimately, is only a matrix multiplication:

$$\vec{S}_{out,i} = M \cdot \vec{S}_{in}$$

where the 16 elements of M are functions of the frequency and position

- What is the best way to model M:
  - Physically motivated parameterization from the full master equation ?
  - Fully effective approach with no a priori information ?

- This project aims at answering these questions for the RAHWP

Expertise of the team

IJCLab group:

- Sophie Henriot-Versillé
- Matthieu Tristram
- Stephane Ilic

APC group:

- Josquin Errard
- Ema Tsang King Sang (PhD student)

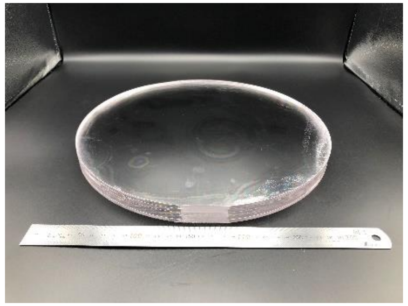
- Lead the IMo team
- Instrument calibration (MHFT side)
- Data management and simulations
- Involved in the all aspects of data analysis
- Including HWP effects in component separation (Verges et al. (2020))
- Modeling the HWP contribution for SO

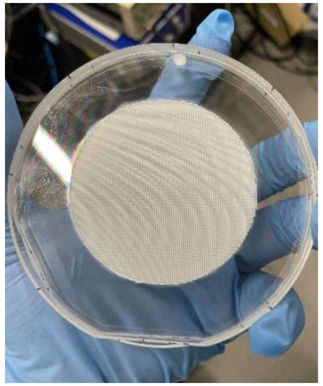
Expertise of the team

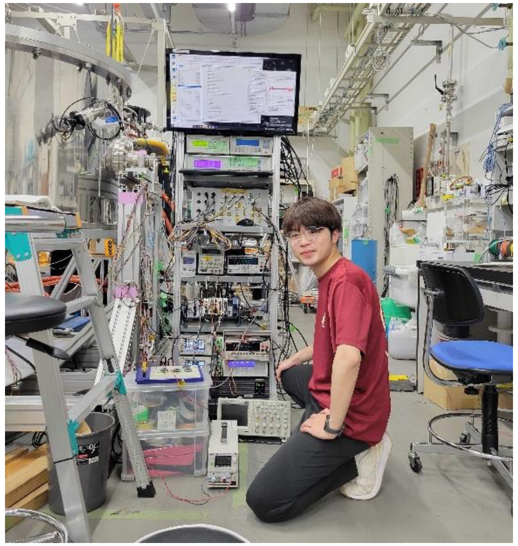
IPMU group:

- Clément Leloup (PI)
- Tomotake Matsumura
- Ryosuke Akizawa (Master student)
- Kosuke Aizawa (Master student)

- ➢ Leading the foreground modeling and component separation work
- ➢ Instrument calibration (LFT side)
- ➢ In charge of the LFT PMU system
- ➢ Started to bridge instrument development and data analysis (e.g. Leloup et al. (2023))







Schedule

2024 Q2	2024 Q3	2024 Q4	2025 (JFY)
- Realistic HWP simulations - Characterization of HWP/PMU properties - Extended data model	- Trip to France - Input from PMU/HWP dev. in the data model - Extension of instrument simulation	- Trip to Japan - Validate extension of the data model - First results from the full pipeline	- Full exploitation of the analysis pipeline with extended data model - Derivation of requirements for instrumental design and calibration - Reiterate the process with other elements (beams, detector systems, ...)